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# Search for supersymmetry in events with one lepton and multiple jets exploiting the angular correlation between the lepton and the missing transverse momentum in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

CERN, Switzerland

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## ABSTRACT

Results are presented from a search for supersymmetry in events with a single electron or muon and hadronic jets. The data correspond to a sample of proton–proton collisions at  $\sqrt{s} = 13$  TeV with an integrated luminosity of  $35.9 \text{ fb}^{-1}$ , recorded in 2016 by the CMS experiment. A number of exclusive search regions are defined according to the number of jets, the number of b-tagged jets, the scalar sum of the transverse momenta of the jets, and the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. Standard model background events are reduced significantly by requiring a large azimuthal angle between the direction of the lepton and of the reconstructed W boson, computed under the hypothesis that all of the missing transverse momentum in the event arises from a neutrino produced in the leptonic decay of the W boson. The numbers of observed events are consistent with the expectations from standard model processes, and the results are used to set lower limits on supersymmetric particle masses in the context of two simplified models of gluino pair production. In the first model, where each gluino decays to a top quark–antiquark pair and a neutralino, gluino masses up to 1.8 TeV are excluded at the 95% CL. The second model considers a three-body decay to a light quark–antiquark pair and a chargino, which subsequently decays to a W boson and a neutralino. In this model, gluinos are excluded up to 1.9 TeV.

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## 1. Introduction

Supersymmetry (SUSY) [1–8] is a promising extension of the standard model (SM) of particle physics. The addition of supersymmetric partners to the SM particles can lead to the suppression of quadratically divergent loop corrections to the mass squared of the Higgs boson [9]. Furthermore, in SUSY models with  $R$ -parity conservation [10], the lightest supersymmetric particle (LSP) can provide a dark matter candidate [11,12].

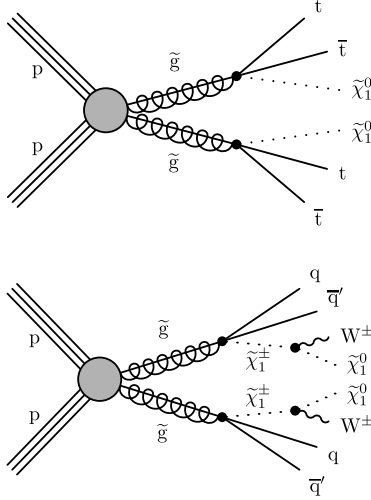
This paper presents a search for SUSY in the single-lepton channel using data recorded in 2016 by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  of proton–proton collisions at  $\sqrt{s} = 13$  TeV. The analysis is an update of the search in Ref. [13], which was performed using the significantly smaller data sample collected by CMS in 2015. Similar searches were performed by the CMS and ATLAS experiments at  $\sqrt{s} = 7$  TeV [14–16], 8 TeV [17–19], and 13 TeV [20–22].

The results are interpreted within the framework of simplified models [23–26] of gluino pair production in which the LSP is the lightest neutralino,  $\tilde{\chi}_1^0$ , and the lepton is produced in the decay of a W boson that originates either from top-quark (t) or chargino ( $\tilde{\chi}_1^\pm$ ) decay. In the T1tttt model shown in Fig. 1 (upper), gluinos ( $\tilde{g}$ ) undergo three-body decays to  $t\bar{t} + \tilde{\chi}_1^0$ . In the T5qqqqWW model shown in Fig. 1 (lower), the gluinos undergo three-body decays to a first- or second-generation quark–antiquark pair ( $q\bar{q}'$ ) and a  $\tilde{\chi}_1^\pm$ . The chargino is assumed to have mass  $m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$  and to decay to a  $\tilde{\chi}_1^0$  and a W boson.

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).



**Fig. 1.** Diagrams showing the simplified models (upper) T1tttt and (lower) T5qqqqWW.

and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [27]. In what follows, the azimuthal angle around the counterclockwise beam axis is denoted by  $\phi$ .

### 3. Event reconstruction and simulation

The analysis makes use of the particle-flow event algorithm [28], which reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

The degree of isolation of a lepton from other particles provides a strong indication of whether it was produced within a jet, as would be expected from the fragmentation of a  $b$  quark, or in the leptonic decay of a  $W$  boson, which can be produced either directly or in decays of heavy particles such as the top quark. The isolation is characterized by the scalar sum of the transverse momenta ( $p_T$ ) of all particles within a cone of radius  $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  around the lepton momentum vector, excluding the contribution of the lepton and the contribution of charged particles not associated with the primary interaction vertex. In the calculation of the isolation variable, an area-based correction is employed to remove the contribution of particles from “pileup” [29], i.e. additional proton–proton collisions within the same or neighboring bunch crossings. The isolation variable  $I_{\text{rel}}$  is defined as the ratio of the scalar sum of the  $p_T$  in the cone to the transverse momentum of the lepton,  $p_T^\ell$ . To maintain high efficiency for signal events, which can

contain a large number of jets from the SUSY decay chains, a cone radius that depends on  $p_T^\ell$ , is used:  $R = 0.2$  for  $p_T^\ell < 50$  GeV,  $10/p_T^\ell$  [GeV] for  $50 < p_T^\ell < 200$  GeV, and  $0.05$  for  $p_T^\ell > 200$  GeV. This  $p_T$  dependent isolation definition additionally reduces the accidental overlap between jets and the lepton in regions where the SUSY decay products are boosted. Accepted muons and electrons are required to satisfy  $I_{\text{rel}} < 0.2$  and  $I_{\text{rel}} < 0.1$ , respectively.

Jets are clustered using the anti- $k_T$  algorithm [30] with a distance parameter of  $0.4$  [31], as implemented in the FASTJET package [32]. The momentum of a jet, which is determined as the vectorial sum of all particle momenta in the jet, is found from simulation to be within 5 to 10% of the true momentum over the full  $p_T$  spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from pileup [29]. Jet energy corrections are derived from simulation and confirmed with in-situ measurements of the energy balance in di-jet,  $Z$ +jets, and photon+jet events [33]. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions. They have negligible impact on the efficiency for signal events. Jets originating from  $b$  quarks are identified with an inclusive combined secondary vertex tagging algorithm (CSVv2) [34,35] that uses both secondary-vertex and track-based information. The working point is chosen to provide a  $b$  tagging efficiency of  $\approx 63\%$ , a  $c$  tagging efficiency of  $\approx 12\%$ , and a light-flavor and gluon misidentification rate of  $\approx 0.9\%$  for jets with  $p_T > 20$  GeV in simulated  $t\bar{t}$  events [35]. Double counting of objects is avoided by not considering jets that lie within a cone of radius  $0.4$  around a selected lepton. To avoid double counting of objects as both a lepton and a jet, jets that lie within a cone of radius  $R = 0.4$  of a lepton are not considered.

The missing transverse momentum vector,  $\vec{p}_T^{\text{miss}}$ , is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particle-flow objects in an event. Jet energy corrections are propagated to  $\vec{p}_T^{\text{miss}}$ . Its magnitude is referred to as  $p_T^{\text{miss}}$ .

To estimate corrections to transfer factors extracted from data, and to determine certain small backgrounds, Monte Carlo (MC) simulation is used. The leading-order (LO) event generators MADGRAPH5\_AMC@NLO v.2.2.2 or v.2.3.3 [36] are used to simulate  $t\bar{t}$ +jets,  $W$ +jets,  $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$  events, in the following referred to as DY+jets, and multijet events, in the following named QCD events. Events with a single top quark in the final state are generated using the next-to-leading order (NLO) POWHEGv2.0 and POWHEG programs [37–41] for the  $t$ -channel and  $tW$  production, respectively. The  $s$ -channel single-top process and the production of both  $t\bar{t}W$  and  $t\bar{t}Z$ , commonly referred to as  $t\bar{t}V$ , are simulated using the NLO MADGRAPH5\_AMC@NLO v.2.2.2 generator [36]. The simulated background samples are normalized using the most accurate cross section calculations available [36,40–50], which generally correspond to NLO or next-to-NLO (NNLO) precision. All signal events are generated with MADGRAPH5\_AMC@NLO v.2.2.2, with up to two final-state partons in addition to the gluino pair. MADGRAPH5\_AMC@NLO uses the NNPDF3.0LO and the NNPDF3.0NLO PDF [51] for processes with LO or NLO accuracy, respectively. Gluino decays are based on a unit matrix element [52], with signal production cross sections computed at NLO with next-to-leading-logarithm (NLL) accuracy [53–57].

Several benchmark SUSY models, corresponding to different scenarios for the gluino and neutralino masses, are used to study the kinematic properties of the signal and to illustrate the numbers of events expected from SUSY. The benchmarks are denoted by the model name and the two key parameters, namely  $m_{\tilde{g}}$  and  $m_{\tilde{\chi}_1^0}$ . As example, T1tttt(1.4, 1.1) corresponds to the T1tttt model with  $m_{\tilde{g}} = 1.4$  TeV and  $m_{\tilde{\chi}_1^0} = 1.1$  TeV. A second benchmark, T1tttt(1.9, 0.1), is also used in this analysis. Similarly, two benchmark points

are used to study the T5qqqqWW model: T5qqqqWW(1.9, 0.1) and T5qqqqWW(1.5, 1.0). For the two T5qqqqWW benchmark models, the mass of the intermediate chargino is taken to be 1.0 TeV and 1.25 TeV, respectively.

The evolution and hadronization of partons is performed using PYTHIA 8.212 [52] with the CUETP8M1 tune [58]. Pileup is generated for a nominal distribution in the number of pp interactions per bunch crossing, which is subsequently reweighted to match the corresponding distribution observed in data. The detector response for all backgrounds is modeled using a detailed simulation based GEANT4 [59], while a fast simulation program [60] is used to reduce computation time for signal events. The fast simulation has been validated against detailed GEANT4-based simulations in reconstructed objects relevant to this search, and corresponding efficiency corrections based on data are applied to simulated background and signal events, respectively.

#### 4. Trigger and event selection

This analysis requires events containing a loosely isolated electron or muon with  $p_T > 15$  GeV and a scalar sum of the jet transverse momenta in the event,  $H_T$ , with values greater than 400 GeV at the trigger level. To maximize the overall efficiency, additional trigger paths were added requiring missing transverse momentum ( $p_T^{\text{miss}} > 100, 110, \text{ or } 120$  GeV), isolated leptons ( $p_T > 27$  GeV for electrons and  $p_T > 24$  GeV for muons) or leptons with no isolation requirement but with a higher  $p_T$  threshold ( $p_T > 105$  GeV or  $p_T > 115$  GeV for electrons and  $p_T > 50$  GeV for muons). The trigger efficiency is measured in control samples recorded either with single-lepton triggers or with triggers with a requirement on  $H_T$ . After applying the offline event selection requirements, an overall trigger efficiency of  $(98 \pm 1)\%$  is observed for the electron channel and negligible inefficiency for the muon channel.

The event selection is similar to that presented in Ref. [13], with improvements as noted to enhance the sensitivity of the analysis. Leptons (electrons or muons) must satisfy  $p_T > 25$  GeV. Additional leptons with  $p_T > 10$  GeV that satisfy looser selection criteria of  $I_{\text{rel}} < 0.4$  are referred to as “veto” leptons. To reduce the contribution from standard model processes that produce higher lepton multiplicities, events with one or more veto leptons are rejected.

Jets are required to have  $p_T > 30$  GeV and  $|\eta| < 2.4$  to be considered for the calculation of higher level quantities such as  $H_T$ , the number of jets ( $n_{\text{jet}}$ ), and the number of b-tagged jets ( $n_b$ ). A number of exclusive kinematic regions, denoted as “search bins”, are defined according to  $n_{\text{jet}}$ ,  $n_b$ ,  $H_T$ , and the quantity  $p_T^\ell + p_T^{\text{miss}}$  ( $L_T$ ). All search bins are required to contain at least five jets with the two highest- $p_T$  jets satisfying  $p_T > 80$  GeV. Search bins with zero b-tagged jets, called “0-b”, are mainly sensitive to the T5qqqqWW model, while search bins with at least one b-tagged jet, called “multi-b”, are mainly sensitive to the T1tttt model. For the latter, the requirement on the number of jets is increased to six, since the presence of four top quarks results in an increased jet multiplicity in signal events.

To ensure that the analysis is sensitive both to signals with high  $p_T^{\text{miss}}$  as well as with small  $p_T^{\text{miss}}$  but with large lepton  $p_T$ , no explicit threshold on  $p_T^{\text{miss}}$  is imposed. Instead,  $L_T$  is required to be  $> 250$  GeV. Because of the trigger requirements and the extensive jet activity expected in the chosen SUSY models,  $H_T$  is required to be  $> 500$  GeV.

An important background arises from  $t\bar{t}$ +jets events in which both W bosons decay leptonically and one lepton does not fulfill the selection criteria for veto leptons. In an extension of the previous analysis [13], and to suppress this background, events containing at least one isolated high- $p_T$  charged track are rejected

in certain cases. The high- $p_T$  track can arise from  $\tau \rightarrow \nu_\tau + \text{hadron}$  decays or muon or electron tracks of poor quality. The relative isolation of such tracks within a cone of  $R = 0.3$  around the track candidate is required to be smaller than 0.1 or 0.2 for hadron or lepton particle-flow candidates, respectively. For events containing such isolated track candidates, the  $M_{T2}$  variable [61] is used:

$$M_{T2}(\vec{p}_T^\ell, \vec{p}_T^t, \vec{p}_T^{\text{miss}}) = \min_{\vec{p}_T^{(1)} + \vec{p}_T^{(2)} = \vec{p}_T^{\text{miss}}} \left\{ \max \left[ M_T(\vec{p}_T^\ell, \vec{p}_T^{(1)}), M_T(\vec{p}_T^t, \vec{p}_T^{(2)}) \right] \right\},$$

where  $\vec{p}_T^\ell$  and  $\vec{p}_T^t$  are the transverse momenta of the isolated track and the selected lepton respectively, and  $M_T$  is the transverse mass. The minimization runs over all possible splittings of  $\vec{p}_T^{\text{miss}}$  assuming two lost massless particles, as in dileptonic  $t\bar{t}$  decays that contain two neutrinos. The isolated track with highest  $p_T$  and opposite charge relative to the selected lepton is chosen where  $\vec{p}_T^t$  is required to be  $> 5$  GeV. Events with a hadronic or leptonic isolated track with  $M_{T2}$  below 60 or 80 GeV, respectively, are rejected. This requirement removes approximately 40% of dilepton  $t\bar{t}$ +jets events, while rejecting only 8–15% of the events in the SUSY benchmark models.

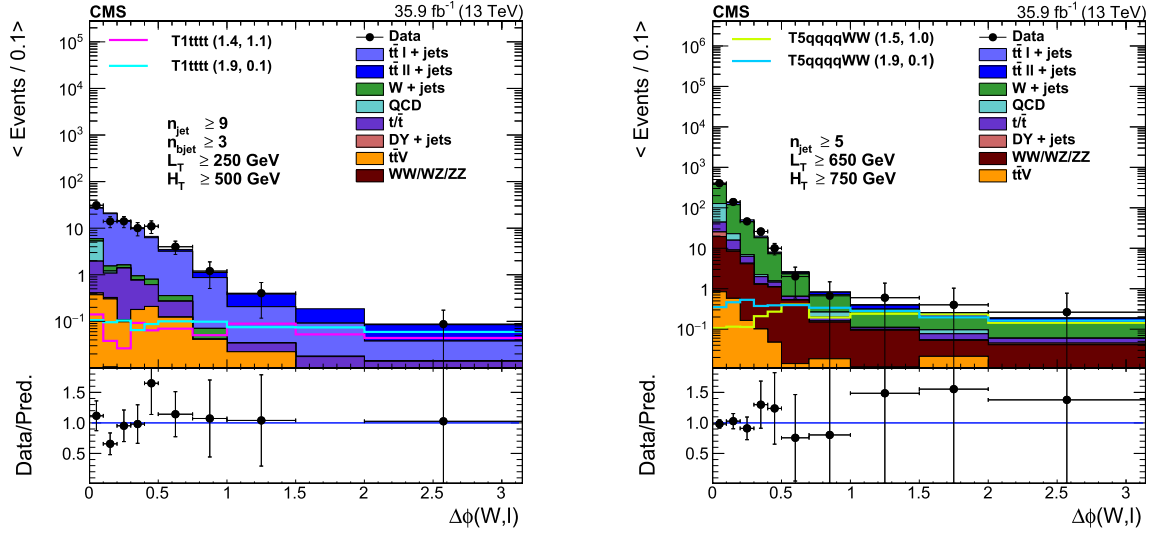
After these selections, the dominant remaining backgrounds are W+jets events in which the W boson decays leptonically, and  $t\bar{t}$ +jets events in which one of the W bosons from the top quarks decays leptonically and the other W boson decays hadronically. Both backgrounds are suppressed by requiring a large azimuthal angle  $\Delta\phi$  between the lepton and the presumed W boson. The transverse momentum of the leptonically decaying W boson is estimated as the sum of  $\vec{p}_T^\ell$  and  $\vec{p}_T^{\text{miss}}$  vectors. In background events from W+jets and  $t\bar{t}$ +jets with a single W-boson’s leptonic decay, the  $\Delta\phi$  distribution falls sharply and has a maximum value determined by the mass and  $p_T$  of the W boson. In the SUSY models investigated here,  $\vec{p}_T^{\text{miss}}$  receives a large contribution from the two neutralino LSPs. As a consequence, large values of  $\Delta\phi$  are possible and the resulting  $\Delta\phi$  distribution in signal events is roughly uniform. The  $\Delta\phi$  variable can therefore be used to define the search region (SR) as events with large  $\Delta\phi$ , while events with small  $\Delta\phi$  constitute the control region (CR), which is used to estimate the SM background in the SR. For illustration, Fig. 2 shows the  $\Delta\phi$  distributions in two tightened multi-b and 0-b search bins as defined in Table 6. The magnitude of the angle between the W boson and the lepton is inversely proportional to the W boson momentum, which at high  $p_T$  is approximated by  $L_T$ . Therefore, the  $\Delta\phi$  threshold used in defining the SR varies between 0.5 and 1, depending on  $L_T$ .

The definitions of the search bins, along with the  $\Delta\phi$  values selected for the SRs, are given in Tables 4 and 5 for the multi-b and 0-b analyses, respectively. The name convention assigns a letter to each  $n_{\text{jet}}$  and  $n_b$  category and a number from 0 up to 10 for each  $H_T$  and  $L_T$  selection. The multi-b and the 0-b analysis employ 39 and 28 search bins, respectively.

#### 5. Background estimation

The method for estimating the background from SM processes is the same as the one presented in Ref. [13]. For completeness, a summary of the procedure is presented below.

The dominant backgrounds in all search bins arise from semi-leptonically decaying  $t\bar{t}$  and leptonic W+jets events. In each search bin, the number of background events in the SR, i.e. the yield of events at high  $\Delta\phi$ , is determined using the number of events in the CR, i.e. the events at low  $\Delta\phi$ , along with a transfer factor  $R_{\text{CS}}$  that relates the events observed in the CR,  $N_{\text{data}}(\text{CR})$ , to those expected in the SR,  $N_{\text{data}}(\text{SR})$ , as  $R_{\text{CS}} = N_{\text{data}}(\text{SR})/N_{\text{data}}(\text{CR})$ .



**Fig. 2.** Comparison of the  $\Delta\phi$  distribution for (left) the multi-b and (right) the 0-b analysis for two of the search bins given in Table 6. The simulated background events are stacked on top of each other and several signal points are overlaid for illustration. The wider bins are normalized to a bin width of 0.1. The ratio of data to simulation is given in the lower panels. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

**Table 1**

Overview of the definitions of the various regions and samples employed in the analysis. For the QCD fit the electron (e) sample is used, while for the determination (det.) of  $R_{CS}(W^\pm)$  the muon ( $\mu$ ) sample is used. Regions corresponding to blank cells are not used in the analysis.

| Analysis         | Multi-b analysis           |               | 0-b analysis   |                              |
|------------------|----------------------------|---------------|--|------------------------------|
|                  | $n_b = 0$                  | $n_b \geq 1$  | $n_b = 0$  | $n_b \geq 1$                 |
| $n_{jet} = 3$    | QCD bkg. fit<br>(e sample) | $R_{CS}$ det. | $R_{CS}(W^\pm)$ det. ( $\mu$ sample),<br>QCD bkg. fit (e sample) | $R_{CS}(t\bar{t}+jets)$ det. |
| $n_{jet} = 4$    |                            |               |  |                              |
| $n_{jet} = 5$    |                            |               | search bins  |                              |
| $n_{jet} \geq 6$ |                            | search bins   |  |                              |

This transfer factor is measured in kinematic regions in data with a lower number of jets,  $n_{jet}$ , where the contribution from the signal is negligible. Potential residual differences in transfer factors in the low- and high- $n_{jet}$  regions are determined through simulation, where a correction factor, denoted by  $\kappa$ , is determined for each search bin as  $\kappa = R_{CS}^{MC}(\text{high-}n_{jet})/R_{CS}^{MC}(\text{low-}n_{jet})$ .

In the multi-b analysis, the regions with one b tag and four or five jets consist of approximately 80%  $t\bar{t}$ +jets and 15–20% W+jets and single top quark events. In all other multi-b regions the  $t\bar{t}$  background is dominant. For this reason, only one transfer factor is calculated in the CRs with four or five jets to account for all backgrounds except QCD for each  $L_T$ ,  $H_T$  and  $n_b$  range. This factor is then used to estimate the background in each SR of the search bins with  $n_{jet} \in [6-8]$  or  $n_{jet} \geq 9$ . A single transfer factor is used for the  $n_b \geq 2$  search bins with the same  $H_T$  and  $L_T$ , since these factors are found to be essentially independent of  $n_b$ .

In the 0-b search bins, the contributions from W+jets and  $t\bar{t}$ +jets are roughly equal, and a transfer factor for each background is determined in each of the search bins in  $n_{jet}$ ,  $H_T$ , and  $L_T$ . The transfer factor for  $t\bar{t}$ +jets events is measured in data using events with  $n_{jet} \in [4, 5]$  and  $n_b \geq 1$ . For W+jets events, the transfer factor is measured also in data in events with  $n_{jet} \in [3, 4]$  and  $n_b = 0$ ; the jet multiplicity used for W+jets is lower than in  $t\bar{t}$ +jets to limit the contamination from  $t\bar{t}$ +jets events. The relative contribution of the  $t\bar{t}$ +jets and W+jets components in the CR of each search bin is determined by a fit of the  $n_b$  multiplicity distribution in the CR of the high- $n_{jet}$  regions, using templates of the  $n_b$  multiplicity distributions for W+jets and  $t\bar{t}$ +jets that are obtained from simulation. Additional backgrounds, including those from single top quark production, are found to be small and are taken from simulation.

About 10–15% of the SM background events in the electron channel CRs are expected to be QCD, and arise mainly from jets misidentified as electrons or from photon conversions in the tracker. In the SRs, however, the QCD background has been found to be negligible. It is estimated from data, using “antiselected” events in which the electrons fail the criteria for selected electrons but satisfy looser identification and isolation requirements. These events are scaled by the ratio of jets and photons that pass the tight electron-identification requirements to the number of antiselected electron candidates in a QCD-enriched sample that consists of no b-tagged jets and three or four jets. To account for the QCD background in the data, the QCD background is subtracted from the number of events in the CR in the calculation of the transfer factor  $R_{CS}$  as well as from the number of events in the CR in each search bin. The prediction of the number of events in the SR of each search bin is then defined as:

$$N_{pred}(SR) = R_{CS}\kappa \left[ N_{data}^{high-n_{jet}}(CR) - N_{QCD pred}^{high-n_{jet}}(CR) \right].$$

The various  $(n_{jet}, n_b)$  regions employed in the analysis are described in Table 1.

## 6. Systematic uncertainties

The systematic uncertainties are divided into two categories: those that affect the estimate of the background from SM processes, and those that affect the expected signal yields.

The main systematic uncertainty on the background estimate arises from the uncertainty on the value of the transfer factor  $R_{CS}$ . The latter is measured in low- $n_{jet}$  data but is then applied in the



search bins that have higher jet multiplicities. The modeling of jets from initial-state radiation (ISR) is obtained from a data sample populated mainly by dilepton  $t\bar{t}$ +jets events. This sample is defined by two opposite-sign leptons (electrons or muons), excluding events with same-flavor leptons within a window of  $\pm 10$  GeV around the Z-boson mass, and two b-tagged jets, such that any other remaining jets are interpreted as ISR. In simulation, all jets that cannot be matched to daughter particles from the hard interaction are treated as ISR jets. The difference between the number of ISR jets observed and simulated is then used to reweight simulated  $t\bar{t}$ +jets events in all analysis selections. The reweighting factors vary between 0.92 and 0.51 for  $N_{j_{\text{ISR}}}$  between 1 and 6. We take one half of the deviation from unity as the systematic uncertainty on these reweighting factors.

The presence of two neutrinos in dilepton  $t\bar{t}$ +jets events tends to produce larger angles between the lepton and the presumed W boson than in single-lepton  $t\bar{t}$ +jets events. As a result, the fraction of dilepton  $t\bar{t}$ +jets in which the second lepton does not pass the veto lepton requirements, is larger at high  $\Delta\phi$  values, i.e. in the SR, than in the CR. This fraction as a function of  $n_{\text{jet}}$  must be described well in the simulation, as the differences in the transfer factors between the low- $n_{\text{jet}}$  and high- $n_{\text{jet}}$  events, i.e. the  $\kappa$  factors, are determined in simulation. This assumption is tested using dilepton events, selected as described in the previous paragraph and split into a 0-b and a multi-b category. To study the behavior of the background from dilepton events that remain in the single-lepton selection because of the loss of one lepton, one of the two leptons is removed from the event. Since in this type of background, the lost leptons arise principally from  $\tau \rightarrow \text{hadrons} + \nu$  decays, and to account for the  $p_{\text{T}}^{\text{miss}}$  due to the neutrino from the  $\tau$  decay, the lepton removed is replaced by a jet with 2/3 of the  $p_{\text{T}}$  of the original lepton and the  $L_{\text{T}}$ ,  $\Delta\phi$ , and  $H_{\text{T}}$  values are recalculated for the resulting “single-lepton” event. To maximize the number of events in the dilepton  $t\bar{t}$ +jets control sample, no  $\Delta\phi$  requirement is applied, and all events are used twice, with each reconstructed lepton considered as the lost lepton. The jet multiplicity in the single-lepton baseline selection (excluding the SR) is compared with that in the corresponding simulated event sample. In addition, the jet multiplicity in the dilepton  $t\bar{t}$ +jets control sample in data is compared with the corresponding simulated event sample. From these two comparisons a double-ratio is formed. The remaining differences in the double-ratio, which are of the order of 3–6% per  $n_{\text{jet}}$  bin, are corrected through the calculated  $\kappa$  factors, and propagated as a systematic uncertainty.

Uncertainties in the background estimate that also affect the signal arise from uncertainties in the jet energy scale (JES) [31], from uncertainties in the scale factors correcting the efficiencies and misidentification rate for b tagging [35], and from uncertainties in the reconstruction and identification efficiencies of leptons [62,63].

In each case, the systematic uncertainty in the background is estimated by changing the corresponding correction factors within their uncertainties. After each such change in the JES, the  $H_{\text{T}}$  and  $p_{\text{T}}^{\text{miss}}$  in each event are recalculated. Similarly, the uncertainty arising from pileup is estimated by varying the inelastic cross section by its 5% uncertainty [64].

The W+jets and  $t\bar{t}$ +jets cross sections are varied independently by 30% [65] to account for possible biases in the estimation of the background composition in terms of W+jets vs.  $t\bar{t}$ +jets events, which changes slightly the value of  $\kappa$ . These changes have only a small impact on the 0-b analysis, where the relative fraction of the two processes is determined from a fit. In the multi-b analysis, the differences in the  $\kappa$  values of less than 3% are propagated to the background estimates. The  $t\bar{t}$ V cross section is varied by 100%. The

**Table 2**

Summary of systematic uncertainties in the total background estimates for the multi-b and for the 0-b analyses.

| Source                               | Uncertainty for multi-b [%] | Uncertainty for 0-b [%] |
|--------------------------------------|-----------------------------|-------------------------|
| Dilepton control sample              | 0.9–7.0                     | 0.3–18                  |
| JES                                  | 0.3–18                      | 0.7–26                  |
| Tagging of b jets                    | 0.1–0.9                     | 0.1–2.5                 |
| Mistagging of light flavor jets      | 0.1–2.2                     | 0.3–0.8                 |
| $\sigma(W+\text{jets})$              | 0.3–9.3                     | 0.3–10                  |
| $\sigma(t\bar{t})$                   | 0.1–7.5                     | 0.7–13                  |
| $\sigma(t\bar{t}V)$                  | 0.2–20                      | 0.1–3.8                 |
| W polarization                       | 0.1–3.3                     | 0.7–14                  |
| ISR reweighting ( $t\bar{t}$ )       | 0.5–7.0                     | 0.2–11                  |
| Pileup                               | 0.4–7.1                     | 0.1–20                  |
| Statistical uncertainty in MC events | 5–30                        | 5–36                    |

**Table 3**

Summary of the systematic uncertainties and their average effect on the yields for the benchmark points defined in the text. The values, which are quite similar for the multi-b and the 0-b analyses, are usually larger for compressed scenarios, where the mass difference between the gluino and the lightest neutralino is small.

| Source                              | Uncertainty [%] |
|-------------------------------------|-----------------|
| Trigger                             | 2               |
| Pileup                              | 10              |
| Lepton efficiency                   | 2               |
| Isolated track veto                 | 4               |
| Luminosity                          | 2.5             |
| ISR                                 | 2–25            |
| Tagging of b jets                   | 1–6             |
| Mistagging of light flavor jets     | 1–4             |
| JES                                 | 3–40            |
| Factorization/renormalization scale | 1–3             |
| $p_{\text{T}}^{\text{miss}}$        | 2–20            |

systematic uncertainty in the QCD background depends on  $n_{\text{jet}}$  and  $n_{\text{b}}$ , and ranges from 25% up to 100% for the highest  $n_{\text{b}}$  region.

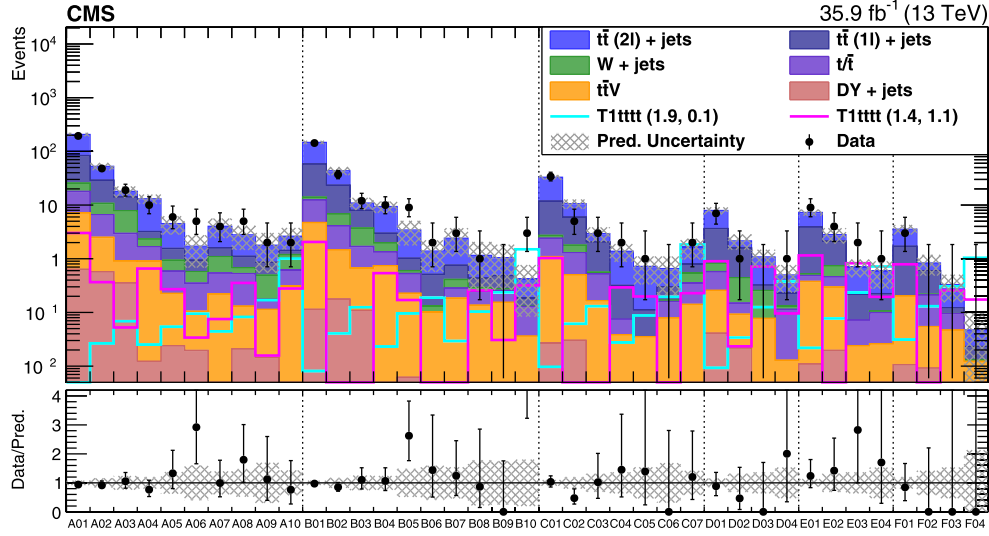
The polarization of W bosons is changed by reweighting events by the factor  $w(\cos\theta^*) = 1 + \alpha(1 - \cos\theta^*)^2$ , where  $\theta^*$  is the angle between the charged lepton and W boson in the W boson rest frame. For W+jets events, we use  $\alpha = 0.1$ , guided by the measurements and theoretical uncertainties [66–69]. For  $t\bar{t}$ +jets events, we use  $\alpha = 0.05$  [70–73]. For W+jets events, where the initial state can have different polarizations for  $W^+$  and  $W^-$  bosons, the uncertainty is determined by the larger change in  $\kappa$  resulting from reweighting only the  $W^+$  bosons in the sample, and from reweighting all W bosons.

For the 0-b analysis, an additional systematic uncertainty is based on linear fits of  $R_{\text{CS}}$  as a function of  $n_{\text{jet}}$  that are found to describe the dependence within statistical uncertainties. A 50% cross section uncertainty is used for all backgrounds other than W+jets,  $t\bar{t}$ +jets,  $t\bar{t}V$ , and QCD.

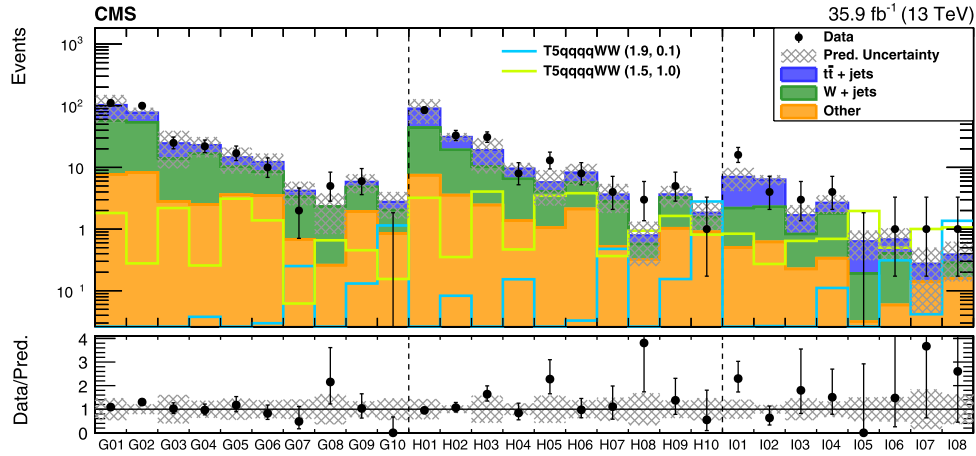
For the signal, an uncertainty in ISR is applied using the approach described previously for the reweighting of the distribution of ISR jets in  $t\bar{t}$ +jets as both, signal and  $t\bar{t}$ +jets, rely on MADGRAPH5\_AMC@NLO for event generation. Half of the correction is used as an estimate of the uncertainty as is propagated to the signal acceptance. To gauge their impact, the factorization and renormalization scales are changed up and down by a factor of 2.

Finally, the luminosity is measured using the pixel cluster counting method [74], with the absolute luminosity obtained using Van der Meer scans. The resulting uncertainty is estimated to be 2.5% [75].

The impact of the systematic uncertainties on the estimate of the total background in the multi-b and 0-b analyses is summarized in Table 2. While systematic uncertainties are determined for each signal point, typical values for most signals are summarized for illustration in Table 3.



**Fig. 3.** Multi-b search: comparison of the numbers of events observed in the data and the numbers expected from the estimated SM backgrounds in the 39 search bins defined in the text, with details given in Table 4. Upper panel: the data are represented by black points with error bars, while the total SM background expected is shown as a hatched region that represents the uncertainty. For illustration, the relative fraction of the different SM background contributions determined in simulation is shown by the stacked, colored histograms, normalized so that their sum is equal to the background estimated using data control regions, as described in the text. The expected event yields for two T1tttt SUSY benchmark models are represented by the open histograms. Lower panel: the ratio of the number of events observed in data to the number of events expected from the SM background in each search bin. The error bars on the data points indicate the statistical uncertainty in the ratio, while the gray hatched region indicates the uncertainty on this ratio from the uncertainty in the background estimate.



**Fig. 4.** 0-b search: comparison of the numbers of events observed in the data and the numbers expected from the estimated SM backgrounds in the 28 search bins defined in the text, with details given in Table 5. Upper panel: the data are represented by black points with error bars, while the total SM background expected is shown as a hatched region that represents the uncertainty. The filled, stacked histograms represent the predictions for  $t\bar{t}$ +jets, W+jets events, and the remaining backgrounds. The expected yields from two T5qqqqWW SUSY benchmark models are represented as solid lines. Lower panel: the ratio of the number of events observed in data to the number of events expected from the SM background in each search bin. The error bars on the data points indicate the statistical uncertainty in the ratio, while the gray hatched region indicates the uncertainty on this ratio from the uncertainty in the background estimate.

## 7. Results and interpretation

The data in the search regions are compared to the background estimates in Fig. 3 for the multi-b events, where the outline of the filled histogram represents the total estimated number of background events. For illustration, the expected composition of the background is shown, assuming the relative fractions of the different SM processes ( $t\bar{t}$ +jets, W+jets, and other backgrounds), as determined from simulation.

Fig. 4 displays the estimates and data observed in the 0-b events. The filled histogram represents the estimates from data for  $t\bar{t}$ +jets and W+jets events and the remaining backgrounds, which include the QCD estimate determined from data and rare backgrounds determined from simulation.

To facilitate the reinterpretation of the results in terms of models not considered here, a comparison of the background estimates and the observed number of events in the SR of a few aggregated search bins is presented in Table 6. The results for all bins, compared to two benchmark points, are given in Tables 4 and 5 for the multi-b and 0-b analyses, respectively. The data agree with the expectations from the SM and no significant excess is observed.

The absence of any significant excess consistent with the SUSY signals considered in the analysis is used to set limits in the parameter space of the gluino and lightest neutralino masses. Separate likelihood functions, one for the multi-b analysis and one for the 0-b analysis, are constructed from the Poisson probability functions for the CR and SR at both high and low jet multiplicities. This includes the  $\kappa$  values that correct any residual differences in

**Table 4**

Definition of search bins and naming convention in the multi-b search. Also given are the  $\Delta\phi$  values that are used to define the CRs and the SRs, the numbers of expected background events with combined statistical and systematic uncertainties, the observed numbers of events, and the expected numbers of signal events in the multi-b search bins.

| $n_{\text{jet}}$ | $n_b$    | $L_T$<br>[GeV] | $\Delta\phi$<br>[rad] | $H_T$<br>[GeV] | Bin<br>name | Signal T1tttt ( $m_{\tilde{g}}, m_{\tilde{\chi}^0_1}$ ) [TeV] |                 | Predicted<br>background | Observed<br>data |
|------------------|----------|----------------|-----------------------|----------------|-------------|---|-----------------|-------------------------|------------------|
|                  |          |                |                       |                |             | (1.9, 0.1)  | (1.4, 1.1)      |                         |                  |
| [6, 8]           | =1       | [250, 450]     | 1.0                   | [500, 1000]    | A01         | <0.01   | $3.02 \pm 0.24$ | $206 \pm 15$            | 194              |
|                  |          |                |                       | [1000, 1500]   | A02         | $0.03 \pm 0.01$   | $0.37 \pm 0.08$ | $52.5 \pm 8.2$          | 48               |
|                  |          |                |                       | $\geq 1500$    | A03         | $0.07 \pm 0.01$   | $0.05 \pm 0.03$ | $18.0 \pm 4.2$          | 19               |
|                  |          | [450, 600]     | 0.75                  | [500, 1000]    | A04         | $0.03 \pm 0.01$   | $0.66 \pm 0.11$ | $13.1 \pm 2.7$          | 10               |
|                  |          |                |                       | [1000, 1500]   | A05         | $0.05 \pm 0.01$   | $0.27 \pm 0.07$ | $4.5 \pm 1.7$           | 6                |
|                  |          |                |                       | $\geq 1500$    | A06         | $0.09 \pm 0.01$   | $0.03 \pm 0.02$ | $1.7 \pm 1.0$           | 5                |
|                  |          | [600, 750]     | 0.5                   | [500, 1000]    | A07         | $0.04 \pm 0.01$   | $0.08 \pm 0.04$ | $4.0 \pm 1.6$           | 4                |
|                  |          |                |                       | [1000, 1500]   | A08         | $0.08 \pm 0.01$   | $0.35 \pm 0.08$ | $2.8 \pm 1.3$           | 5                |
|                  |          |                |                       | $\geq 1500$    | A09         | $0.17 \pm 0.02$   | $0.02 \pm 0.02$ | $1.8 \pm 1.2$           | 2                |
|                  |          | $\geq 750$     | 0.5                   | $\geq 500$     | A10         | $1.01 \pm 0.04$   | $0.28 \pm 0.07$ | $2.6 \pm 1.1$           | 2                |
|                  | =2       | [250, 450]     | 1.0                   | [500, 1000]    | B01         | $0.01 \pm 0.01$   | $2.06 \pm 0.20$ | $147 \pm 11$            | 143              |
|                  |          |                |                       | [1000, 1500]   | B02         | $0.04 \pm 0.01$   | <0.01           | $43.5 \pm 7.5$          | 37               |
|                  |          |                |                       | $\geq 1500$    | B03         | $0.13 \pm 0.01$   | <0.01           | $10.9 \pm 2.8$          | 12               |
|                  |          | [450, 600]     | 0.75                  | [500, 1000]    | B04         | $0.02 \pm 0.01$   | $0.54 \pm 0.10$ | $9.4 \pm 2.2$           | 10               |
|                  |          |                |                       | [1000, 1500]   | B05         | $0.10 \pm 0.01$   | $0.17 \pm 0.06$ | $3.4 \pm 1.7$           | 9                |
|                  |          |                |                       | $\geq 1500$    | B06         | $0.19 \pm 0.02$   | <0.01           | $1.39 \pm 0.82$         | 2                |
|                  |          | [600, 750]     | 0.5                   | [500, 1000]    | B07         | $0.03 \pm 0.01$   | <0.01           | $2.4 \pm 1.3$           | 3                |
|                  |          |                |                       | [1000, 1500]   | B08         | $0.10 \pm 0.01$   | $0.26 \pm 0.07$ | $1.16 \pm 0.90$         | 1                |
|                  |          |                |                       | $\geq 1500$    | B09         | $0.24 \pm 0.02$   | $0.03 \pm 0.02$ | $1.05 \pm 0.78$         | 0                |
|                  |          | $\geq 750$     | 0.5                   | $\geq 500$     | B10         | $1.50 \pm 0.05$   | $0.32 \pm 0.08$ | $0.42 \pm 0.34$         | 3                |
|                  | $\geq 3$ | [250, 450]     | 1.0                   | [500, 1000]    | C01         | $0.01 \pm 0.01$   | $1.03 \pm 0.14$ | $32.9 \pm 3.3$          | 34               |
|                  |          |                |                       | [1000, 1500]   | C02         | $0.06 \pm 0.01$   | <0.01           | $10.6 \pm 2.1$          | 5                |
|                  |          |                |                       | $\geq 1500$    | C03         | $0.13 \pm 0.01$   | <0.01           | $2.93 \pm 0.91$         | 3                |
|                  |          | [450, 600]     | 0.75                  | [500, 1000]    | C04         | $0.03 \pm 0.01$   | $0.29 \pm 0.07$ | $1.38 \pm 0.50$         | 2                |
|                  |          |                |                       | [1000, 1500]   | C05         | $0.09 \pm 0.01$   | $0.20 \pm 0.06$ | $0.72 \pm 0.39$         | 1                |
|                  |          |                |                       | $\geq 1500$    | C06         | $0.20 \pm 0.02$   | <0.01           | $0.66 \pm 0.45$         | 0                |
|                  |          | $\geq 600$     | 0.5                   | $\geq 500$     | C07         | $1.85 \pm 0.05$   | $0.23 \pm 0.06$ | $1.66 \pm 0.69$         | 2                |
| $\geq 9$         | =1       | [250, 450]     | 1.0                   | [500, 1500]    | D01         | $0.01 \pm 0.01$   | $0.90 \pm 0.12$ | $7.9 \pm 1.1$           | 7                |
|                  |          |                |                       | $\geq 1500$    | D02         | $0.03 \pm 0.01$   | $0.02 \pm 0.02$ | $2.15 \pm 0.67$         | 1                |
|                  |          | $\geq 450$     | 0.75                  | [500, 1500]    | D03         | $0.13 \pm 0.01$   | $0.72 \pm 0.11$ | $1.08 \pm 0.39$         | 0                |
|                  |          |                |                       | $\geq 1500$    | D04         | $0.38 \pm 0.02$   | $0.10 \pm 0.04$ | $0.50 \pm 0.27$         | 1                |
|                  | =2       | [250, 450]     | 1.0                   | [500, 1500]    | E01         | $0.02 \pm 0.01$   | $1.15 \pm 0.14$ | $7.26 \pm 0.97$         | 9                |
|                  |          |                |                       | $\geq 1500$    | E02         | $0.08 \pm 0.01$   | <0.01           | $2.81 \pm 0.89$         | 4                |
|                  |          | $\geq 450$     | 0.75                  | [500, 1500]    | E03         | $0.23 \pm 0.02$   | $0.83 \pm 0.12$ | $0.71 \pm 0.26$         | 2                |
|                  |          |                |                       | $\geq 1500$    | E04         | $0.72 \pm 0.03$   | $0.20 \pm 0.05$ | $0.59 \pm 0.31$         | 1                |
|                  | $\geq 3$ | [250, 450]     | 1.0                   | [500, 1500]    | F01         | $0.03 \pm 0.01$   | $0.79 \pm 0.11$ | $3.55 \pm 0.72$         | 3                |
|                  |          |                |                       | $\geq 1500$    | F02         | $0.13 \pm 0.01$   | <0.01           | $0.83 \pm 0.35$         | 0                |
|                  |          | $\geq 450$     | 0.75                  | [500, 1500]    | F03         | $0.31 \pm 0.02$   | $0.26 \pm 0.06$ | $0.33 \pm 0.17$         | 0                |
|                  |          |                |                       | $\geq 1500$    | F04         | $1.04 \pm 0.04$   | $0.17 \pm 0.05$ | $0.05 \pm 0.05$         | 0                |

the  $R_{\text{CS}}$  transfer factors for regions with different jet multiplicities. As discussed previously, the values of  $\kappa$  are obtained from simulation, and their uncertainties are incorporated in the likelihood through log-normal constraints. The estimated contribution from QCD events in the CR is also included. A possible signal contamination, which can be up to 10% for the shown benchmark points, is taken into account by including signal terms in the likelihood for both the low- $n_{\text{jet}}$  regions as well as for the low- $\Delta\phi$  CR of the search bins. For the 0-b analysis, the relative contributions from W+jets and  $t\bar{t}$ +jets events determined in the fits to the  $n_b$  distribution in the CR are treated as external measurements. The correlation between the W+jets and  $t\bar{t}$ +jets production that is introduced by such fits is also taken into account. A “profile” likelihood ratio is used as test statistic. The limits at the 95% confidence level (CL) are calculated using the asymptotic formulae [76] of the CL<sub>s</sub> criterion [77,78].

The 95% CL upper limits on the cross sections, set in the T1tttt model using the multi-b analysis, and in the T5qqqqWW model using the 0-b analysis, are shown in Fig. 5. Using the  $\tilde{g}\tilde{g}$  pair production cross section calculated at NLO within NLL accuracy, exclusion limits are provided as a function of the  $(m_{\tilde{g}}, m_{\tilde{\chi}^0_1})$  mass hy-

pothesis for the data and for the simulation. For neutralino masses below 800 GeV, gluino masses up to 1.8 TeV are excluded at the 95% CL in the T1tttt model. Neutralinos are excluded up to 1.1 TeV for gluino masses below 1.7 TeV. In the T5qqqqWW model, gluino masses up to 1.9 TeV are excluded at the 95% CL for neutralino masses below 300 GeV. Neutralinos are excluded up to 950 GeV for gluino masses below 1.2 TeV.

## 8. Summary

A search for supersymmetry has been performed using a  $35.9\text{fb}^{-1}$  sample of proton–proton collisions at  $\sqrt{s} = 13\text{TeV}$ , recorded by the CMS experiment in 2016. Several exclusive search bins are defined that differ in the number of jets, the number of b-tagged jets, the scalar sum of all jet transverse momenta as well as the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. The main background processes, which arise from W+jets and  $t\bar{t}$ +jets in a final state with exactly one lepton and multiple jets, is reduced significantly by requiring a large azimuthal angle between the direction of the lepton and of the reconstructed W boson, computed under the hypothesis



**Table 5**

Definition of search bins and naming convention in the 0-b search. Also given are the  $\Delta\phi$  values that are used to define the CRs and the SRs, the numbers of expected background events with combined statistical and systematic uncertainties, the observed numbers of events, and the expected numbers of signal events in the 0-b search bins.

| $n_{\text{jet}}$ | $L_T$<br>[GeV] | $\Delta\phi$<br>[rad] | $H_T$<br>[GeV]                           | Bin<br>name | Signal T5qqqqWW ( $m_{\tilde{g}}, m_{\tilde{\chi}^0}$ ) [TeV] |                 | Predicted<br>background | Observed<br>data |
|------------------|----------------|-----------------------|--|-------------|---|-----------------|-------------------------|------------------|
|                  |                |                       |  |             | (1.5, 1.0)  | (1.9, 0.1)      |                         |                  |
| 5                | [250, 350]     | 1.0                   | [500, 750]<br>$\geq 750$                 | G01         | $1.82 \pm 0.29$   | $<0.01$         | $102 \pm 48$            | 111              |
|                  |                |                       |  | G02         | $0.21 \pm 0.09$   | $0.01 \pm 0.01$ | $77 \pm 16$             | 100              |
|                  | [350, 450]     | 1.0                   | [500, 750]<br>$\geq 750$                 | G03         | $2.25 \pm 0.32$   | $<0.01$         | $24 \pm 15$             | 25               |
|                  |                |                       |  | G04         | $0.29 \pm 0.11$   | $0.04 \pm 0.01$ | $22.8 \pm 8.3$          | 22               |
|                  | [450, 650]     | 0.75                  | [500, 750]<br>[750, 1250]<br>$\geq 1250$ | G05         | $3.02 \pm 0.37$   | $<0.01$         | $14.5 \pm 6.5$          | 17               |
|                  |                |                       |  | G06         | $1.40 \pm 0.25$   | $0.04 \pm 0.02$ | $12.1 \pm 4.7$          | 10               |
|                  |                |                       |  | G07         | $0.08 \pm 0.06$   | $0.25 \pm 0.04$ | $4.2 \pm 1.7$           | 2                |
|                  | $\geq 650$     | 0.5                   | [500, 750]<br>[750, 1250]<br>$\geq 1250$ | G08         | $0.74 \pm 0.18$   | $0.01 \pm 0.01$ | $2.3 \pm 1.5$           | 5                |
|                  |                |                       |  | G09         | $0.49 \pm 0.15$   | $0.12 \pm 0.03$ | $5.8 \pm 2.0$           | 6                |
|                  |                |                       |  | G10         | $0.14 \pm 0.07$   | $1.15 \pm 0.08$ | $2.7 \pm 1.3$           | 0                |
| [6, 7]           | [250, 350]     | 1.0                   | [500, 1000]<br>$\geq 1000$               | H01         | $3.02 \pm 0.36$   | $<0.01$         | $89 \pm 38$             | 85               |
|                  |                |                       |  | H02         | $0.31 \pm 0.10$   | $0.09 \pm 0.02$ | $30.9 \pm 5.1$          | 33               |
|                  | [350, 450]     | 1.0                   | [500, 1000]<br>$\geq 1000$               | H03         | $4.13 \pm 0.41$   | $0.01 \pm 0.01$ | $19 \pm 11$             | 31               |
|                  |                |                       |  | H04         | $0.52 \pm 0.14$   | $0.14 \pm 0.03$ | $9.5 \pm 2.3$           | 8                |
|                  | [450, 650]     | 0.75                  | [500, 750]<br>[750, 1250]<br>$\geq 1250$ | H05         | $3.63 \pm 0.39$   | $<0.01$         | $5.7 \pm 3.3$           | 13               |
|                  |                |                       |  | H06         | $3.79 \pm 0.39$   | $0.03 \pm 0.01$ | $8.2 \pm 3.2$           | 8                |
|                  |                |                       |  | H07         | $0.36 \pm 0.12$   | $0.47 \pm 0.05$ | $3.6 \pm 1.8$           | 4                |
|                  | $\geq 650$     | 0.5                   | [500, 750]<br>[750, 1250]<br>$\geq 1250$ | H08         | $0.89 \pm 0.19$   | $<0.01$         | $0.79 \pm 0.53$         | 3                |
|                  |                |                       |  | H09         | $1.77 \pm 0.26$   | $0.15 \pm 0.03$ | $3.6 \pm 1.4$           | 5                |
|                  |                |                       |  | H10         | $0.83 \pm 0.18$   | $2.83 \pm 0.12$ | $1.83 \pm 0.86$         | 1                |
| $\geq 8$         | [250, 350]     | 1.0                   | [500, 1000]<br>$\geq 1000$               | I01         | $0.88 \pm 0.18$   | $<0.01$         | $7.0 \pm 2.8$           | 16               |
|                  |                |                       |  | I02         | $0.26 \pm 0.09$   | $0.03 \pm 0.01$ | $6.3 \pm 1.2$           | 4                |
|                  | [350, 450]     | 1.0                   | [500, 1000]<br>$\geq 1000$               | I03         | $0.55 \pm 0.14$   | $<0.01$         | $1.67 \pm 0.77$         | 3                |
|                  |                |                       |  | I04         | $0.72 \pm 0.15$   | $0.11 \pm 0.02$ | $2.65 \pm 0.89$         | 4                |
|                  | [450, 650]     | 0.75                  | [500, 1250]<br>$\geq 1250$               | I05         | $2.07 \pm 0.26$   | $0.01 \pm 0.01$ | $0.63 \pm 0.32$         | 0                |
|                  |                |                       |  | I06         | $0.45 \pm 0.12$   | $0.3 \pm 0.04$  | $0.68 \pm 0.35$         | 1                |
|                  | $\geq 650$     | 0.5                   | [500, 1250]<br>$\geq 1250$               | I07         | $0.97 \pm 0.18$   | $0.04 \pm 0.01$ | $0.27 \pm 0.23$         | 1                |
|                  |                |                       |  | I08         | $1.12 \pm 0.18$   | $1.37 \pm 0.08$ | $0.38 \pm 0.24$         | 1                |

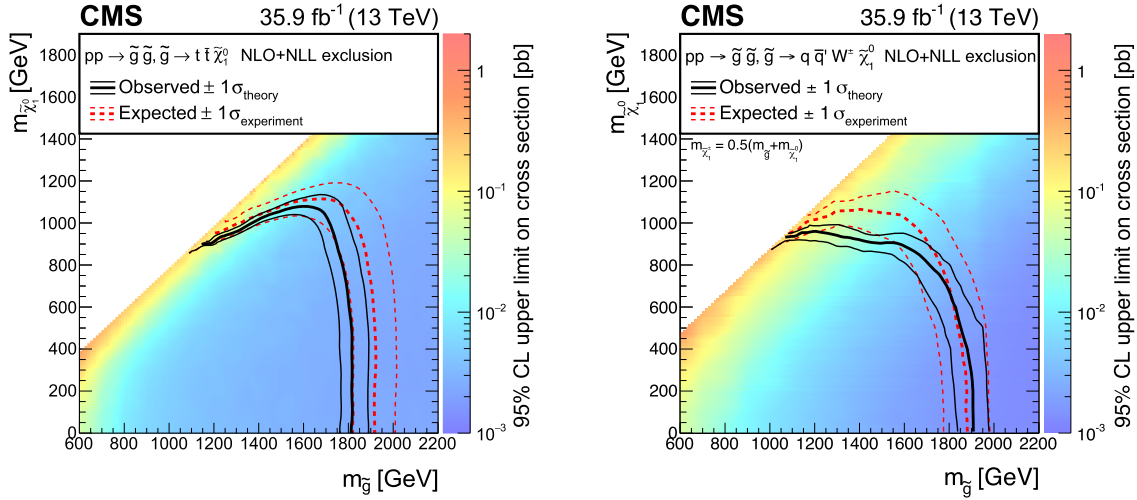
**Table 6**

Numbers of expected background events with combined statistical and systematic uncertainty and the observed numbers of events in aggregated search bins. The expected number of signal events for the two corresponding benchmark signals for the multi-b and 0-b analyses, respectively, are given as well.

| $n_b$    | $n_{\text{jet}}$ | $L_T$<br>[GeV] | $\Delta\phi$<br>[rad] | $H_T$<br>[GeV] | Signal T1tttt ( $m_{\tilde{g}}, m_{\tilde{\chi}^0}$ ) [TeV]   |                 | Predicted<br>background | Observed<br>data |
|----------|------------------|----------------|-----------------------|----------------|---|-----------------|-------------------------|------------------|
|          |                  |                |                       |                | (1.4, 1.1)  | (1.9, 0.1)      |                         |                  |
| $\geq 1$ | $\geq 6$         | $\geq 600$     | 0.5                   | $\geq 1000$    | $2.66 \pm 0.30$   | $7.39 \pm 0.14$ | $11.2 \pm 3.6$          | 13               |
| $\geq 3$ | $\geq 6$         | $\geq 600$     | 0.5                   | $\geq 1000$    | $0.48 \pm 0.12$   | $3.07 \pm 0.09$ | $0.84 \pm 0.48$         | 1                |
| $\geq 2$ | $\geq 9$         | $\geq 450$     | 0.75                  | $\geq 500$     | $1.35 \pm 0.20$   | $2.34 \pm 0.08$ | $1.61 \pm 0.43$         | 3                |
| $\geq 2$ | $\geq 9$         | $\geq 450$     | 0.75                  | $\geq 1500$    | $0.37 \pm 0.10$   | $1.79 \pm 0.07$ | $0.64 \pm 0.33$         | 1                |
| $\geq 3$ | $\geq 9$         | $\geq 250$     | 1.0                   | $\geq 500$     | $1.12 \pm 0.19$   | $1.33 \pm 0.06$ | $4.58 \pm 0.83$         | 3                |
| $\geq 3$ | $\geq 9$         | $\geq 250$     | 1.0                   | $\geq 1500$    | $0.12 \pm 0.05$   | $1.02 \pm 0.05$ | $0.81 \pm 0.33$         | 0                |
| $\geq 3$ | $\geq 9$         | $\geq 450$     | 0.75                  | $\geq 500$     | $0.41 \pm 0.11$   | $1.37 \pm 0.06$ | $0.37 \pm 0.17$         | 0                |
| $\geq 3$ | $\geq 9$         | $\geq 450$     | 0.75                  | $\geq 1500$    | $0.17 \pm 0.07$   | $1.06 \pm 0.05$ | $0.05 \pm 0.05$         | 0                |
|          |                  |                |                       |                | Signal T5qqqqWW ( $m_{\tilde{g}}, m_{\tilde{\chi}^0}$ ) [TeV] |                 |                         |                  |
|          |                  |                |                       |                | (1.5, 1.0)  | (1.9, 0.1)      |                         |                  |
| 0        | $\geq 5$         | $\geq 650$     | 0.5                   | $\geq 750$     | $6.15 \pm 0.57$   | $6.29 \pm 0.20$ | $18.4 \pm 5.1$          | 14               |
| 0        | $\geq 6$         | $\geq 450$     | 0.75                  | $\geq 500$     | $16.59 \pm 0.94$  | $5.28 \pm 0.19$ | $28.8 \pm 6.8$          | 37               |
| 0        | $\geq 6$         | $\geq 650$     | 0.5                   | $\geq 1000$    | $4.01 \pm 0.46$   | $4.98 \pm 0.18$ | $5.1 \pm 1.8$           | 4                |
| 0        | $\geq 7$         | $\geq 450$     | 0.75                  | $\geq 500$     | $9.47 \pm 0.71$   | $3.54 \pm 0.15$ | $9.7 \pm 2.5$           | 11               |
| 0        | $\geq 7$         | $\geq 650$     | 0.5                   | $\geq 500$     | $4.28 \pm 0.48$   | $3.30 \pm 0.15$ | $3.8 \pm 1.2$           | 4                |
| 0        | $\geq 8$         | $\geq 250$     | 1.0                   | $\geq 1250$    | $1.82 \pm 0.31$   | $1.71 \pm 0.11$ | $7.2 \pm 1.9$           | 8                |

that all of the missing transverse momentum in the event arises from a neutrino produced in the leptonic decay of the W boson. The event yields observed in data are in agreement with the standard model background, which is estimated using control regions in data and corrections based on simulation. The lack of any significant excess of events is interpreted in terms of limits on the parameters of two simplified models that describe gluino pair production.

For the T1tttt simplified model, in which each gluino decays to a  $t\bar{t}$  pair and the lightest neutralino, gluino masses up to 1.8 TeV are excluded for neutralino masses below 800 GeV. Neutralino masses below 1.1 TeV are excluded for a gluino mass up to 1.7 TeV. This result extends the exclusion limit from the previous analysis [13] on gluino masses by about 250 GeV. The second simplified model, T5qqqqWW, also describes gluino pair production, but with decays to first- or second-generation quarks and



**Fig. 5.** Cross section limits at a 95% CL for the (left) T1tttt and (right) T5qqqqWW models, as a function of the gluino and LSP masses. In T5qqqqWW, the pair-produced gluinos decay to first- or second-generation quark–antiquark pairs ( $q\bar{q}$ ) and a chargino ( $\tilde{\chi}_1^\pm$ ) with its mass taken to be  $m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$ . The solid black (dashed red) lines correspond to the observed (expected) mass limits, with the thicker lines representing the central values and the thinner lines representing the limits of 68% uncertainty bands related to the theoretical (experimental) uncertainties.

a chargino, which decays to a W boson and the lightest neutralino. The chargino mass in this decay channel is assumed to be  $m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$ . Gluino masses below 1.9 TeV are excluded for neutralino masses below 300 GeV. This corresponds to an improvement of about 500 GeV over the previous result [13]. For a gluino mass of 1.2 TeV, neutralinos with masses up to 950 GeV are excluded.

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## The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöffbeck, M. Spanring, D. Spitzbart, J. Strauss, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup>

Université Libre de Bruxelles, Bruxelles, Belgium



A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

*Ghent University, Ghent, Belgium*

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

N. Beliy

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas<sup>a</sup>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

*Institute for Nuclear Research and Nuclear Energy, Bulgaria Academy of Sciences, Sofia, Bulgaria*

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

*Universidad de Los Andes, Bogota, Colombia*

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*



V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>6</sup>, T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

*University of Cyprus, Nicosia, Cyprus*

M. Finger<sup>7</sup>, M. Finger Jr.<sup>7</sup>

*Charles University, Prague, Czech Republic*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

A. Ellithi Kamel<sup>8</sup>, S. Khalil<sup>9</sup>, A. Mohamed<sup>9</sup>

*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

J.-L. Agram<sup>10</sup>, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>10</sup>, X. Coubez, J.-C. Fontaine<sup>10</sup>, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

S. Gadrat

*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>11</sup>, V. Sordini, M. Vander Donckt, S. Viret

*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

T. Toriashvili <sup>12</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze <sup>7</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl <sup>13</sup>

*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras <sup>14</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo <sup>15</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel <sup>16</sup>, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann <sup>16</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, A. Singh, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

S. Bein, V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo <sup>13</sup>, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann <sup>13</sup>, S.M. Heindl, U. Husemann, F. Kassel <sup>13</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

S. Kesisoglou, A. Panagiotou, N. Saoulidou

*National and Kapodistrian University of Athens, Athens, Greece*

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

*University of Ioánnina, Ioánnina, Greece*

M. Csanad, N. Filipovic, G. Pasztor

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

G. Bencze, C. Hajdu, D. Horvath<sup>17</sup>, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>18</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>19</sup>, A. Makovec, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>18</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Debrecen, Hungary*

S. Choudhury, J.R. Komaragiri

*Indian Institute of Science (IISc), Bangalore, India*

S. Bahinipati<sup>20</sup>, S. Bhowmik, P. Mal, K. Mandal, A. Nayak<sup>21</sup>, D.K. Sahoo<sup>20</sup>, N. Sahoo, S.K. Swain

*National Institute of Science Education and Research, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

*University of Delhi, Delhi, India*

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*

P.K. Behera

*Indian Institute of Technology Madras, Madras, India*

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>13</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

*Tata Institute of Fundamental Research-A, Mumbai, India*

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>22</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>22</sup>, N. Wickramage<sup>23</sup>

*Tata Institute of Fundamental Research-B, Mumbai, India*

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

*Indian Institute of Science Education and Research (IISER), Pune, India*

S. Chenarani<sup>24</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>24</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>25</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>26</sup>, M. Zeinali

*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*

## M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,13</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy<sup>b</sup> Università di Bari, Bari, Italy<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,27</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a,b,13</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>13</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy<sup>b</sup> Università di Genova, Genova, Italy

L. Brianza<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, K. Pauwels<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b,28</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,13</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, W.A. Khan<sup>a</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,13</sup>, P. Paolucci<sup>a,13</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen<sup>a</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy<sup>c</sup> Università della Basilicata, Potenza, Italy<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi<sup>a,13</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy<sup>b</sup> Università di Padova, Padova, Italy<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri<sup>a</sup>, F. Fallavollita<sup>a,b</sup>, A. Magnani<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, C. Cecchi, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsova<sup>a</sup>, P. Azzurri<sup>a,13</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedi<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,27</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,29</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, N. Daci<sup>a</sup>, D. Del Re<sup>a,b,13</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Rome, Italy

<sup>b</sup> Sapienza Università di Roma, Rome, Italy

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P. Traczyk<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte<sup>a</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, A. Zanetti<sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim, D.H. Moon, G. Oh

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea



J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

*Seoul National University, Seoul, Republic of Korea*

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

*University of Seoul, Seoul, Republic of Korea*

Y. Choi, C. Hwang, J. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

V. Dudenas, A. Juodagalvis, J. Vaitkus

*Vilnius University, Vilnius, Lithuania*

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>30</sup>, F. Mohamad Idris<sup>31</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>32</sup>, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler

*University of Canterbury, Christchurch, New Zealand*

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszek<sup>33</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela

*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev<sup>34,35</sup>, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

Y. Ivanov, V. Kim<sup>36</sup>, E. Kuznetsova<sup>37</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

*Institute for Nuclear Research, Moscow, Russia*

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepanov, M. Toms, E. Vlasov, A. Zhokin

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

T. Aushev, A. Bylinkin<sup>35</sup>

*Moscow Institute of Physics and Technology, Moscow, Russia*

M. Chadeeva<sup>38</sup>, O. Markin, P. Parygin, D. Philippov, S. Polikarpov, V. Rusinov

*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*

V. Andreev, M. Azarkin<sup>35</sup>, I. Dremin<sup>35</sup>, M. Kirakosyan<sup>35</sup>, A. Terkulov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>39</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

V. Blinov<sup>40</sup>, Y. Skovpen<sup>40</sup>, D. Shtol<sup>40</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*

P. Adzic<sup>41</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco<sup>42</sup>, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban<sup>16</sup>, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer<sup>13</sup>, M.J. Kortelainen, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic<sup>43</sup>, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi<sup>44</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>45</sup>, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns<sup>46</sup>, G.I. Veres<sup>18</sup>, M. Verweij, N. Wardle, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl<sup>†</sup>, L. Caminada<sup>47</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, A. Zagozdinska<sup>33</sup>, D.H. Zhu

*ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*

T.K. Aarrestad, C. Amsler<sup>48</sup>, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, A. Zucchetta

*Universität Zürich, Zurich, Switzerland*

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

*National Central University, Chung-Li, Taiwan*

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Adiguzel<sup>49</sup>, F. Boran, S. Cerci<sup>50</sup>, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>51</sup>, E.E. Kangal<sup>52</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>53</sup>, K. Ozdemir<sup>54</sup>, D. Sunar Cerci<sup>50</sup>, H. Topakli<sup>55</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*

B. Bilin, G. Karapinar<sup>56</sup>, K. Ocalan<sup>57</sup>, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E. Gülmez, M. Kaya<sup>58</sup>, O. Kaya<sup>59</sup>, S. Tekten, E.A. Yetkin<sup>60</sup>

*Bogazici University, Istanbul, Turkey*

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*

L. Levchuk, P. Sorokin

*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold<sup>61</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>62</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko<sup>6</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>63</sup>, T. Virdee<sup>13</sup>, D. Winterbottom, J. Wright, S.C. Zenz

*Imperial College, London, United Kingdom*

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

*Brunel University, Uxbridge, United Kingdom*

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

*Baylor University, Waco, USA*

R. Bartek, A. Dominguez

*Catholic University of America, Washington DC, USA*

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

*The University of Alabama, Tuscaloosa, USA*

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

*Boston University, Boston, USA*

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

*Brown University, Providence, USA*

R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

*University of California, Davis, Davis, USA*

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

*University of California, Los Angeles, USA*

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

*University of California, Riverside, Riverside, USA*

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>64</sup>, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

*University of California, Santa Barbara – Department of Physics, Santa Barbara, USA*

D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

Y.R. Joshi, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

*Florida International University, Miami, USA*



A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, T. Perry, H. Prosper, A. Saha, A. Santra, R. Yohay

*Florida State University, Tallahassee, USA*

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

*University of Illinois at Chicago (UIC), Chicago, USA*

B. Bilki<sup>65</sup>, W. Clarida, K. Dilsiz<sup>66</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>67</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>68</sup>, Y. Onel, F. Ozok<sup>69</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

*Johns Hopkins University, Baltimore, USA*

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

*The University of Kansas, Lawrence, USA*

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

*Massachusetts Institute of Technology, Cambridge, USA*

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

*State University of New York at Buffalo, Buffalo, USA*

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

*Northeastern University, Boston, USA*

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>34</sup>, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

*Princeton University, Princeton, USA*

S. Malik, S. Norberg

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

*Purdue University, West Lafayette, USA*

T. Cheng, N. Parashar, J. Stupak

*Purdue University Northwest, Hammond, USA*

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

*Rice University, Houston, USA*

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

*University of Rochester, Rochester, USA*

R. Ciesielski, K. Goulianos, C. Mesropian

*The Rockefeller University, New York, USA*

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

*Rutgers, The State University of New Jersey, Piscataway, USA*

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>70</sup>, A. Castaneda Hernandez<sup>70</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>71</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

*Texas A&M University, College Station, USA*

N. Akchurin, J. Damgov, F. De Guio, P.R. Duder, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

*University of Virginia, Charlottesville, USA*

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

*Wayne State University, Detroit, USA*

J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

*University of Wisconsin – Madison, Madison, WI, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

<sup>3</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>4</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>5</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>6</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

<sup>7</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>8</sup> Now at Cairo University, Cairo, Egypt.

<sup>9</sup> Also at Zewail City of Science and Technology, Zewail, Egypt.

<sup>10</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>11</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>12</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>13</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>14</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>15</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>16</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>17</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>18</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>19</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>20</sup> Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

<sup>21</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>22</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>23</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>24</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>25</sup> Also at Yazd University, Yazd, Iran.

<sup>26</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>27</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>28</sup> Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy.

<sup>29</sup> Also at Purdue University, West Lafayette, USA.

<sup>30</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

- <sup>31</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- <sup>32</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- <sup>33</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- <sup>34</sup> Also at Institute for Nuclear Research, Moscow, Russia.
- <sup>35</sup> Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- <sup>36</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>37</sup> Also at University of Florida, Gainesville, USA.
- <sup>38</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- <sup>39</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>40</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>41</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>42</sup> Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy.
- <sup>43</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>44</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>45</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>46</sup> Also at Riga Technical University, Riga, Latvia.
- <sup>47</sup> Also at Universität Zürich, Zurich, Switzerland.
- <sup>48</sup> Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- <sup>49</sup> Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
- <sup>50</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>51</sup> Also at Istanbul Aydin University, Istanbul, Turkey.
- <sup>52</sup> Also at Mersin University, Mersin, Turkey.
- <sup>53</sup> Also at Cag University, Mersin, Turkey.
- <sup>54</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>55</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>56</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>57</sup> Also at Necmettin Erbakan University, Konya, Turkey.
- <sup>58</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>59</sup> Also at Kafkas University, Kars, Turkey.
- <sup>60</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>61</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>62</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>63</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>64</sup> Also at Utah Valley University, Orem, USA.
- <sup>65</sup> Also at Beykent University, Istanbul, Turkey.
- <sup>66</sup> Also at Bingol University, Bingol, Turkey.
- <sup>67</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>68</sup> Also at Sinop University, Sinop, Turkey.
- <sup>69</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>70</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>71</sup> Also at Kyungpook National University, Daegu, Korea.